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FULL LENGTH ARTICLE

Experimental studies on constant mass–volume depletion of gas-condensate systems

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KEYWORDS

Dew point pressure;
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Equation of state

Abstract This paper presents a new empirical model to estimate dew point pressure P_d for gas condensate reservoirs as a function of routinely measured gas analysis and reservoir temperature. The proposed model was developed based on field and laboratory PVT analysis data of 202 gas-condensate fluid samples representing different gas reservoirs and a wide range of gas properties and reservoir temperatures. Statistical error analysis was used to determine the accuracy of the model. The evaluation shows that correlation coefficient, average relative error (ARE), and average absolute relative error (AARE) are 0.9896, −1.1% and 2.58%, respectively. In addition, results of the proposed model were compared with those published in the literature and ensured its success for capturing the physical trend of gas-condensate systems, and consequently is considered as the most reliable one for the petroleum industry. The accuracy of the model has been also compared to the Soave Redlich Kwong equation of state (SRK-EOS) and the Peng Robinson equation of state (PR-EOS). Gas condensate samples have been used to check the validity of the proposed model against EOS.

1. Introduction

A gas-condensate fluid is a natural hydrocarbon mixture that is predominantly gas and has a critical temperature lower than the reservoir temperature and cricondentherm temperature, which identifies a state on the dewpoint boundary, higher than the reservoir temperature. For gas-condensate fluids, the complete process of isothermal retrograde condensation upon the decrease of pressure at reservoir temperature involves the sequence of states; a single phase, dewpoint, increase in the quantity of the liquid phase to a maximum followed by a decrease in the quantity to a second dewpoint, and finally the single phase sequence as relatively low pressures are reached [1].

It should be noted that there are two kinds of dew points with which an engineer is concerned. The first type, or normal dew point, usually occurs at low pressures as dry gas is compressed to the point where a liquid first forms. The second

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type, sometimes called the retrograde dew point, occurs when a gas mixture containing heavy hydrocarbons in solution is depressurized until a liquid is formed. The first type, as applied to condensate mixtures, would normally be below the atmospheric pressure and would be of no interest in reservoir performance. The second type is of great importance for the reasons stated, and is referred to throughout this study without further qualification.

The pressure and temperature in the formation can be measured, but no reliable way, other than laboratory investigation, has been found to estimate the dewpoint pressure (P_d). Since laboratory investigation is laborious and expensive it is desirable to find a reasonably accurate method to predict P_ds from the composition and other readily available properties normally measured in the fluids.

In gas condensate reservoirs, the well-productivity often declines rapidly when the near-wellbore pressure drops below the dew point pressure. Radial compositional-reservoir simulation models are often used to investigate this productivity decrease. These models clearly show that liquid dropout around wellbore causes the productivity decrease. This ring of increased condensation saturation around the wellbore reduces the effective permeability to gas and results in rapid well-productivity decline. Therefore, it is very important to accurately determine the P_d for gas condensate reservoirs. The experimental determination of P_d at the reservoir temperature for gas condensate reservoirs is relatively time consuming, expensive and sometimes subject to many errors. Thus, there is a need for simple yet accurate methods of predicting the dew point of gas condensate reservoirs [2].

The empirical correlations, proposed in different forms (mathematical expression, graphical, or tabulated) for determining the dewpoint pressures of gas-condensate systems, are considered very limited in the literature. In addition, these correlations were developed based on gas-condensate fluid samples obtained from certain reservoirs of specific regions of the world. Due to varying compositions of gas-condensate fluids from reservoirs of different regions, different empirical correlations may provide unacceptable predictions of dewpoint pressures when they are applied to gas-condensate fluids behaving differently from the fluid samples on which they were developed. Most of these empirical correlations are strongly relating the P_d to the gas-condensate fluid composition. Therefore, there is a great interest to evaluate the accuracy of these empirically derived correlations relative to the experimental dewpoint pressure values for the gas-condensate systems.

Literature review indicates the existence of three types of equations: working charts, empirical correlations and equations of state.

2. Working charts

Sage and Olds; studied the behavior of reservoir fluids from the Paloma field and proposed tables for determining P_d. From the information obtained, the influence of composition on the P_d was determined. They found that removal of the intermediate molecular weight components from the mixtures resulted in a considerable increase in the P_d. Their results also indicate that the effect of change in temperature was relatively minor when compared with the effect of modifying the composition by removing the intermediate components. They also investigated oil and gas samples from San Joaquin Valley fields and developed plots for P_d determination. The P_d is a function of gas/oil ratio, temperature and oil API gravity. It was emphasized that this correlation was applicable to the very narrow range of variables covered in their investigation [3].

Kurata and Katz obtained experimental data on volatile hydrocarbon mixtures. Their investigation was to establish a correlation, which could be used to predict critical properties. Although they used 29 data points of P_ds no attempt was made to correlate them with composition [4].

Reamer and Sage attempted to extend the existing correlation to higher gas-to-oil ratio by studying combinations of five different pairs of fluids. Numerous diagrams depicting the effect of temperature and gas-to-oil ratio on P_d were presented. They concluded that, due to complexity of the influence of composition, it was doubtful that a useful correlation could be established [5].

Organick and Golding presented a correlation for predicting the saturation pressures for gas condensate and volatile oil mixtures. The correlation is given in the form of a set of 14 working charts, each comprising a family of curves, which cannot be readily adapted to computer. The correlation was developed from 214 experimental saturation points for gas condensates and volatile crude oil mixtures. They reported a probable error of about 8% for the gas condensate fluids used in their study. They also indicated that pure components and simple mixtures could not always be treated satisfactorily by their correlation. Therefore, if their correlation is used to predict the saturation pressure of a simple mixture of pure components, the predicted saturation pressure will generally be somewhat high [6].

Potsch and Braeuer proposed a novel graphical method for determining the P_d as a backup for visual readings of the total volume (gas and liquid) during a constant composition expansion and the Z-factor. The P_d is determined from a plot of the number of moles in the cell versus pressure. Graphical intersecting of the straight line in the one phase region with the curve in the two phase region yields the P_d. Although this method does not require a window or through-window cell, yet a high accuracy single Z-factor calculation routine is required. Although empirical correlations are simple yet accurate to some extent, but they have not been able to reliably duplicate the temperature behavior of constant composition fluids [7].

3. Empirical correlations

Nemeth and Kennedy developed a mathematical correlation relating the P_d of a hydrocarbon fluid to its composition, temperature and characteristics of the C_{7+} fraction. The correlation is listed in Appendix A. They used 579 data points of P_d (some were determined experimentally and others were collected from the literature) to develop an 11-coefficient correlation by multiple regression. The correlation covers a pressures range from 1270 to 10790 psia, and temperature from 40 to 320 °F [8].

Humoud presented an empirical correlation to predict the P_d of a gas condensate fluid from readily available field data (74 data sets). The correlation relates the P_d of a gas condensate directly to its reservoir temperature, pseudo-reduced pressure and temperature, primary separator gas oil ratio, the

primary separator pressure and temperature, and relative densities of separator gas and heptanes plus fractions, representing different gas condensates of the Middle East [9]. The correlation is listed in Appendix A.

Elsharkawy presented an empirical model to estimate the P_d for gas condensate reservoirs as a function of routinely measured gas analysis and reservoir temperature. The proposed model was developed using the experimentally measured and collected data of 340 data points of gas condensate samples covering a wide range of gas properties and reservoir temperature. They mathematically expressed P_d in terms of reservoir temperature, composition of the mixture, molecular weight and specific gravity of the heptanes plus fraction [2]. The correlation is listed in Appendix A.

Marruffo developed correlations to determine the P_d and C_{7+} content of gas condensate reservoirs. The P_d correlation is a function of production parameters: stock tank condensate gravity, initial producing gas condensate ratio, separator gas specific gravity, and reservoir temperature. Marruffo used 106 gas condensates data points that were validated through mathematical recombination and mass balance [10]. The correlations are listed in Appendix A.

Ovalle presented a correlation using laboratory measurements of P_d and other gas properties of 615 gas condensates with worldwide origins based on initial producing gas/condensate ratio, initial stock-tank oil gravity, and specific gravity of the original reservoir gas [11]. The correlation is listed in Appendix A.

Al-Dhamen presented a study with three different techniques to predict the P_d for gas condensate reservoirs. They are: traditional correlations, non-parametric approaches and artificial neural networks. The developed models are functions of reservoir temperature, gas specific gravity, condensate specific gravity, and gas/oil ratio. A total number of 113 experimental data points of P_d were collected from Middle East fields and were then used to develop the models. The data used for developing the models cover a reservoir temperature from 100 to 309 °F, gas oil ratio from 3321 to 103,536 SCF/STB, gas specific gravity from 0.64 to 0.82 and condensate specific gravity from 0.73 to 0.81. Al-Dhamen estimated that the artificial neural network developed in his study has the best results among all other models [12].

4. Equations of state

Equations of state are properly tuned to match some experimental data for a particular reservoir fluid before it can be used to predict other physical properties for that fluid. The equations of state used to calculate the saturation pressure for reservoir fluids have several forms and have been presented to the petroleum industry, the most widely used; being (SRK-EOS) and (PR-EOS) [13].

SRK-EOS

$$P = \left(\frac{RT}{V-b}\right) - \left(\frac{a\alpha}{V(V+b)}\right) \quad (1)$$

PR-EOS

$$P = \left(\frac{RT}{V-b}\right) - \left(\frac{a\alpha}{V(V+b)+b(V-b)}\right) \quad (2)$$

The difference between SRK-EOS and PR-EOS resulted such that the fugacity, fugacity coefficient and compressibility factor calculated from each of the equations of state are quite different. Accordingly, the results from calculating P_d using SRK-EOS and PR-EOS are not the same. Therefore, the development of a new empirical P_d correlation that can provide better P_d predictions with less limitation and better accuracy is of great interest.

The objective of this study is to evaluate the existing gas-condensate P_d correlations using experimentally obtained PVT fluid data representing gas-condensate reservoirs and to develop a new correlation that should depend only on readily available fluid properties normally measured in the field such as reservoir pressure and temperature, gas/oil ratio, oil relative density, gas relative density, and possibly other easily obtained parameters.

Multiple linear/nonlinear least-squares regression analysis is used to develop the new correlation. In addition, different statistical error analyses are utilized to evaluate the new correlation against the existing empirical correlations in the literature using the experimental P_d data utilized in developing the correlation. Furthermore; the new correlation will be validated using experimental P_d data.

5. Experimental

The dew point pressures were measured for 202 samples of gas condensates using the automated mercury free PVT cell (Picture 1). A constant mass Depletion (CMD) was performed by the Macro-Software which subjected each sample to the reservoir temperature and adjusted the pressure to a value above the reservoir pressure then decreased it gradually till the retrograde liquid built up is formed at which the P_d was determined. The retrograde liquid build up was measured by an Interface Detection System (IDS).

6. Data acquisition

Two hundred and two data points, including the field production data and the results of constant mass expansion (CME) tests performed on gas-condensate fluid samples collected from different regions, were acquired and made available for this study. These data sets, which form the basis of information for this study, were stored as data bank. Each data set included the reservoir pressure and temperature, the operating pressure and temperature of the primary separator, the separator and

Picture 1

Table 1 Ranges of gas-condensate production and PVT data.

Property	Minimum	Mean	Maximum
Dewpoint pressure (psia)	2029.7	3952.9	6239.7
Reservoir pressure (psia)	2322.4	5122.0	10014.7
Reservoir temperature (°F)	165.2	233.6	316.0
Pseudoreduced pressure	3.5	7.5	14.8
Pseudoreduced temperature	1.5	1.8	2.1
Z-factor at separator conditions	0.9212	0.9606	0.9845
Separator gas specific gravity	0.6395	0.7225	0.8577
Gas-oil ratio (scf/SP bbl)	4168	33975	325027
Stock tank oil API gravity	43	52	67
Wellstream Heptanes plus specific gravity	0.7579	0.7688	0.7827
Wellstream Heptanes plus molecular weight	119	141	166

dissolved gas/oil ratio, the separator gas specific gravity relative to air and the heptanes-plus specific gravity. Each data point included also the experimentally determined P_d from the CME test. The results of compositional analyses of all samples were utilized to estimate the pseudocritical properties of the gas-condensate systems. It should be noted that all the collected data were used without excluding or eliminating any data. Table 1 lists the ranges of the main parameters that were used to develop the new correlation, and the properties which characterize the gas-condensate systems.

7. Development of a new dew point pressure correlation

The first step in developing the correlation was to select the parameters that are anticipated to influence the P_d behavior. Two types of independent variables were used to develop the new model. The first type was based on the pressure and temperature, the second type was related to the gas-condensate fluid composition. The relationships of these parameters, on the individual and combined basis, to the P_d were investigated. The most important parameters were selected and the least important ones were excluded from the correlation.

7.1. Regression and statistical analysis

The fundamental concept of regression analysis is to fit a function of independent variables to a given set of data points in order to estimate or predict one dependent variable as accurately as possible. Regression deals with the nature of the relation between these variables. In evaluating the degree of regression, all the error or imprecision is assumed to be in the measurement of one variable called the "dependent", while the other variables are assumed to be precisely known. These precise variables are called the "independent" variables. If only one independent variable is involved then it is called simple regression analysis whereas the name multiple regression analysis is implied if more than one independent variable is present. The selected combination of independent variables is called a "model" which can be either linear or non-linear.

7.2. Nonlinear multiple regression

The nonlinear regression is a procedure that produces least squares or weighted least square estimates of the parameters of a nonlinear model. Nonlinear models are usually more difficult to specify and estimate than linear models. The nonlinear procedure requires a model expression, parameter names, initial guess values of parameters, and derivatives of the model with respect to each parameter.

In some cases, the nonlinear models can be linearized or reduced to linear forms by applying the appropriate transformation of variables. For example, consider the following nonlinear equation:

$$Y = a \cdot X_1^{b_1} \cdot X_2^{b_2} \cdot e^{b_3 X_3}$$

Applying the logarithmic transformation on both sides, can be rewritten as:

$$\ln Y = \ln a + b_1 \ln X_1 + b_2 \ln X_2 + b_3 X_3$$

which reduces to a linear equation that can be treated by the linear multiple regression method.

$$Y = a' + b_1 X_1 + b_2 X_2 + b_3 X_3$$

A general multiple regression model, which relates a dependent variable y to k predictor independent variables, x_1, x_2,..., x_k, is given by the model equation:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + e$$

Table 2 Statistical accuracy of dewpoint pressure correlations for the data used in model development.

Correlation	ARE	AARE	$AARE_{max}$	$AARE_{min}$	S^2	E_{rms}	R
Nemeth and Kennedy	4.19	20.92	60.13	0.03	25.76	26.05	0.1371
Humoud	−0.32	16.22	66.85	0.20	21.85	21.81	0.4175
A.M. Elsharkawy	−11.34	23.39	95.92	0.08	28.69	30.80	0.0219
Marruffo	−11.15	28.19	108.85	2.13	39.92	41.37	0.0316
Ovalle equation	−32.66	36.56	93.41	1.12	25.51	41.41	0.5342
SRK-EOS	−12.85	15.14	74.99	1.89	19.27	23.14	0.6831
PR-EOS	−13.66	15.34	70.02	0.05	19.11	23.46	0.7117
This study	−1.10	2.58	16.87	0.02	4.10	4.24	0.9896

The statistical parameter equations are listed in Appendix B.

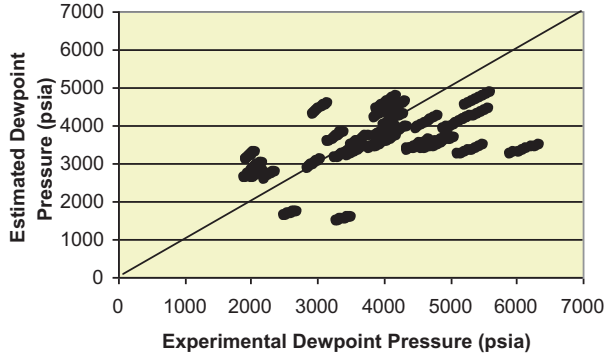

Figure 1 Cross plot of dewpoint pressure correlation (Nemeth and Kennedy).

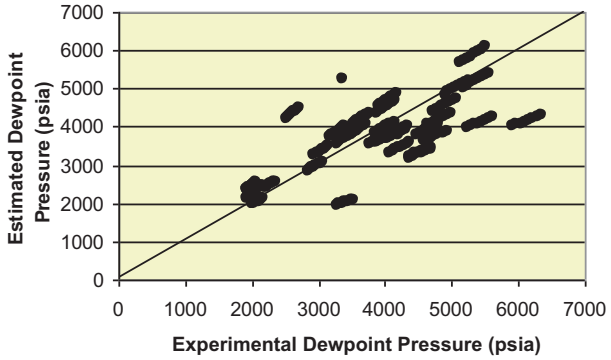

Figure 2 Cross plot of dewpoint pressure correlation (Humoud).

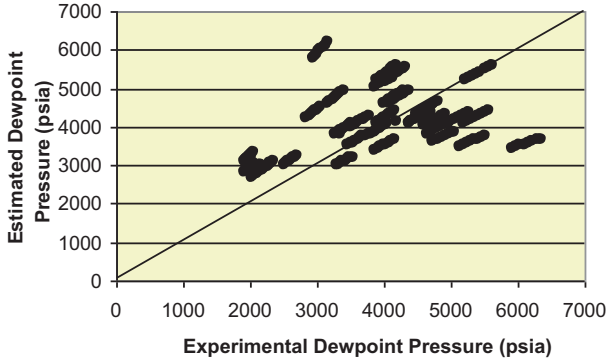

Figure 3 Cross plot of dewpoint pressure correlation (A.M. Elsharkawy).

where α and β are coefficients to be determined by the regression analysis and e is a random error component. The estimated response, y', is obtained from the sample regression equation:

$$y' = a + b_1X_1 + b_2X_2 + \cdots b_kX_k$$

where each regression coefficient β_i, is estimated by b_i from the sample data using the method of least-squares. The errors or deviations between the observed and predicted values are assumed to have a zero mean and unknown variance. Also, it is assumed that the errors are uncorrelated meaning that the value: of one error does not depend on the other error [14]. The n_k equations for the n_k experimental measurements can be expressed in matrix form as:

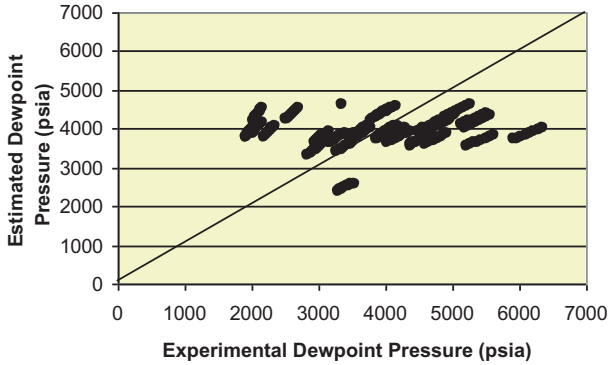

Figure 4 Cross plot of dewpoint pressure correlation (Marruffo).

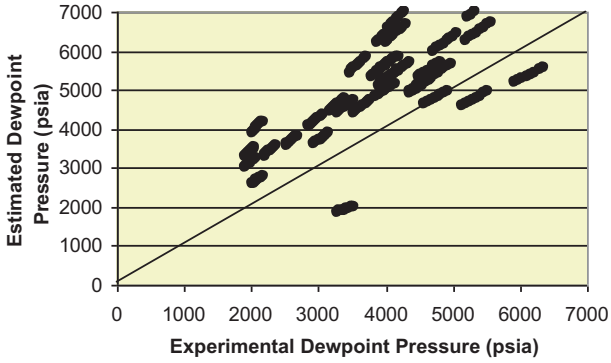

Figure 5 Cross plot of dewpoint pressure correlation (Ovalle).

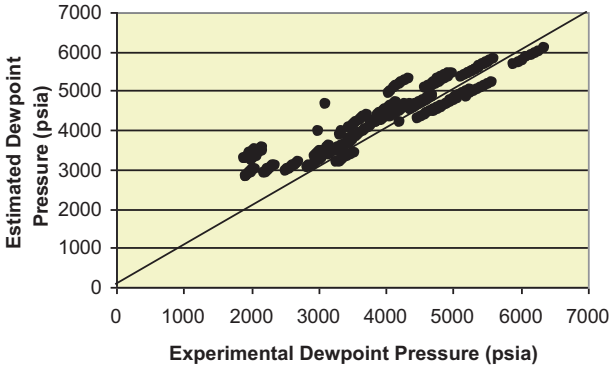

Figure 6 Cross plot of dewpoint pressure equation of state (PR).

$$\begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1n} \\ 1 & x_{21} & x_{22} & \cdots & x_{2n} \cdot x_{31}x_{32}\cdots x_{3n} \cdot \cdots \cdots \cdots \cdots \cdots \\ 1 & x_{n_k1} & x_{n_k2} & \cdots & x_{n_kn} \end{bmatrix}$$

$$[\alpha_1\beta_1\beta_2 \cdots \beta_n] = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \cdot .. \\ y_{n_k} \end{bmatrix}$$

Minimizing routine has resulted in the following correlation equation:

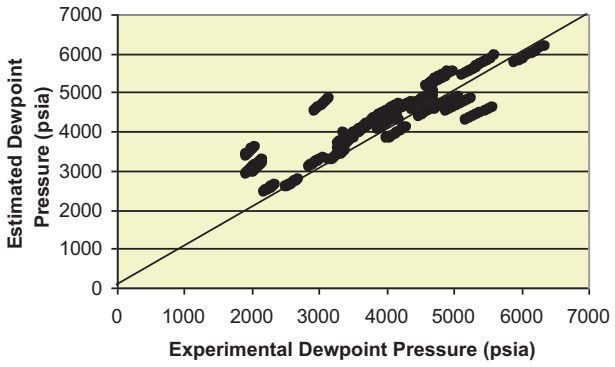

Figure 7 Cross plot of dewpoint pressure equation of state (SRK).

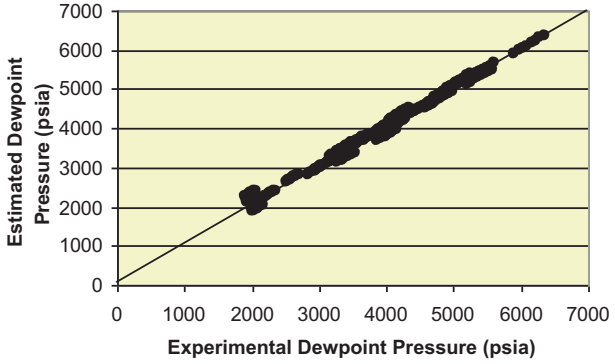

Figure 8 Cross plot of dewpoint pressure correlation (This study).

$$\ln Pd = \beta_0 + \beta_1 \ln(T_R) + \beta_2 \ln(P_{pr}) + \beta_3 \ln(T_{pr}) + \beta_4 \ln(N_{GOR}) + \beta_5 \ln(Z_{sep}) + \beta_6 \ln(N_{C_{7+}})$$

where

$\beta_0 = 11.203$	$P_{pr} = P_R/P_{pc}$, $T_{pr} = T_R/T_{pc}$
$\beta_1 = -0.949$	$P_{pc} = \sum_{i=1}^{n} y_i \cdot P_{ci}$, $T_{pc} = \sum_{i=1}^{n} y_i \cdot T_{ci}$
$\beta_2 = 0.704$	$N_{GOR} = (GOR_{sep}{}^*\gamma_{sep} + GOR_{diss}{}^*\gamma_{diss})/\gamma_{C7+}$
$\beta_3 = 1.135$	$Z_{sep} = \beta_g P_{sep}/(0.028269\ T_{sep})$
$\beta_4 = -0.077$	$\beta_g = (V_g)_{sep}/(V_g)_{sc}$
$\beta_5 = 0.084$	$N_{C7+} = M_{C7+}/\gamma_{C7+}$
$\beta_6 = 0.384$	

8. Result and discussion

Firstly, we examine the accuracy of the proposed model compared to various correlation methods. Secondly, we study the graphical error analysis technique (crossplots) considered in this study for comparative evaluation of the existing correlations with the new correlation and finally we study the validity of the proposed model as compared to these methods.

8.1. Accuracy

Table 2 reports the accuracy of the various methods for predicting the P_d for the gas condensate samples used in this study. It is clear from this table that the new method has the best overall accuracy for the gas condensate samples. The proposed equation has an average absolute relative error (AARE) of 2.58%, average relative error (ARE) of −1.1%, standard deviation (S^2) of 4.1%, the root mean square error of 4.2% and correlation confession (r) of 98.96%.

8.2. Graphical error analysis (Crossplots)

The crossplots of estimated versus experimental values of the dewpoint pressures are shown in Figs. 1–8. For the purpose of accuracy analysis, zero-error line or the 45° line error variances are drawn on these plots.

The cross plot of the newly developed correlation, presented in Fig. 8, shows clearly that the data points are well scattered closely around the 45° line. Overall, the newly developed correlation showed better prediction accuracy and a better error scatter in the data points than the other existing correlations.

8.3. Validity

In order to examine the applicability and reliability of the newly developed empirical correlation of P_d, it was validated using (70) data sets that were not used in the development of the new correlation.

Table 3 summarizes the results of error analysis of the published correlations and the newly developed model. The errors in the existing correlations using the new data sets are considered very close to the errors resulted from the data sets used to develop the new correlation.

Since the new correlation was derived based on data sets that represented gas-condensate systems in different regions, its best performance is expected for the gas-condensate systems of similar properties and conditions. The predictions of the new correlation for the dewpoint pressure were found within less than 3% average absolute error, and with a maximum relative error of less than 17%.

Table 3 Statistical accuracy of P_d correlations for the data used in model development.

Correlation	ARE	AARE	$AARE_{max}$	$AARE_{min}$	S^2	E_{rms}	R
Nemeth and Kennedy	10.26	19.08	60.13	0.03	21.82	23.97	0.1254
Humoud	1.37	13.66	66.85	0.20	18.33	18.25	0.3944
A.M. Elsharkawy	−3.15	20.12	95.92	0.08	25.37	25.38	0.0204
Marruffo	−0.29	20.15	108.85	2.13	30.75	30.53	0.0362
Ovalle	−29.51	33.48	93.41	1.12	24.93	38.52	0.5023
SRK-EOS	−6.88	10.56	74.99	1.89	15.42	16.78	0.7497
PR-EOS	−9.39	11.03	70.02	0.05	15.56	18.08	0.7360
This study	−1.09	2.09	16.87	0.02	3.15	3.31	0.9895

9. Conclusions

Based on the obtained results, the following conclusions are drawn

- A new empirical dewpoint pressure correlation was developed using numerous field production and experimental data. The correlation is a function of reservoir temperature, pseudo reduced pressure and temperature, separator gas/oil ratio, dissolved gas/oil ratio, average specific gravity of separator gas, average specific gravity of dissolved gas, specific gravity of heptanes-plus fraction, super compressibility factor of separator gas and molecular weight of heptanes plus.
- The absolute average relative errors between the results of Nemeth, Humoud, A.M. Elsharkawy, Marruffo and Ovalle correlations show that the average absolute percent relative error was 20.92, 16.22, 23.39, 28.19, and 36.56 respectively and when compared with the SRK-EOS, PR-EOS the results were 15.14 and 15.34, respectively.
- An excellent agreement was obtained between results of the developed new correlation and experimental data with the average absolute percent relative error of 2.58%.

Appendix A. The dew point pressure calculations

A.1. Nemeth and Kennedy correlation

$$\mathrm{Ln}P_d = A_1[y_{C2} + y_{CO2} + y_{H2S} + y_{C6} + 2(y_{C3} + y_{C4}) + y_{C5} + 0.4y_{C1} + 0.2y_{N2}] + A_2\gamma_{C7+} + A_3[y_{C1}/(y_{C1} + 0.002)] + A_4T_R + A_5(y_{C7+}{}^*M_{C7+}) + A_6(y_{C7+}{}^*M_{C7+})^2 + (y_{C7+}{}^*M_{C7+})^3 + A_8[M_{C7+}/(\gamma_{C7+} + 0.0001)] + A_9[M_{C7+}/(\gamma_{C7+} + 0.0001)]^2 + A_{10}[M_{C7+}/(\gamma_{C7+} + 0.0001)]^3 + A_{11}$$

A_1	−2.06230540E + 00	A_7	7.42999510E−05
A_2	6.62597280E + 00	A_8	−1.13811950E−01
A_3	−4.46705590E − 03	A_9	6.24764970E−04
A_4	1.04483460E − 04	A_{10}	−1.07168660E−06
A_5	3.26737140E − 02	A_{11}	1.07466220E + 01
A_6	−3.64532770E−03		

A.2. Humoud correlation

$$\ln P_d = \beta_0 + \beta_1\ln(T_R) + \beta_2\ln(R_m) + \beta_3\ln(P_{sep}.T_{sep}) + \beta_4/T_{pr} + \beta_5/P_{pr} + \beta_6/\gamma_{C7+}$$

β_0	43.777183	β_4	−4.291404
β_1	−3.594131	β_5	−3.698703
β_2	−0.247436	β_6	−4.590091
β_3	−0.053526	$R_m = R_{sep}.\gamma_{sep}/\gamma_{C7+}$	

A.3. El-Sharkawy correlation

$$P_d = A_0 + A_1T_R + A_2\,y_{H2S} + A_3\,y_{CO2} + A_4\,y_{N2} + A_5\,y_{C1} + A_6\,y_{C2} + A_7\,y_{C3} + A_8\,y_{C4} + A_9\,y_{C5} + A_{10}\,y_{C6} + A_{11}\,y_{C7+} + A_{12}\,M_{C7+} + A_{13}\gamma_{C7+} + A_{14}(y_{C7+}{}^*M_{C7+}) + A_{15}(M_{C7+}/\gamma_{C7+}) + A_{16}(y_{C7+}{}^*M_{C7+}/\gamma_{C7+}) + A_{17}(y_{C7}/y_{C1} + y_{C2}) + A_{18}(y_{C7+}/y_{C3} + y_{C4} + y_{C5} + y_{C6})$$

A_0	4268.85	A_{10}	691.5298
A_1	0.094056	A_{11}	40660.36
A_2	−7157.87	A_{12}	205.26
A_3	−4540.58	A_{13}	−7260.32
A_4	−4663.55	A_{14}	−352.413
A_5	−1357.56	A_{15}	−114.519
A_6	−7776.1	A_{16}	8.133
A_7	−9967.99	A_{17}	94.916
A_8	−4257.1	A_{18}	238.252
A_9	−1417.1		

A.4. Marruffo Correlation

$$P_d = K_1{}^*[\mathrm{GOR}_{sep}/Y_{C7+}{}^{K_3}{}^*K_8{}^*\mathrm{API}\hat{}(K_4T_R{}^{K_5} - K_6Y_{C7+}{}^{K_7})]$$

K_1	346.7764689	K_5	0.281255219
K_2	0.094139	K_6	0.00068358
K_3	−0.294782419	K_7	1.906328237
K_4	−0.047833243	K_8	8.417626216

$$\%\,Y_{C7+} = (\mathrm{GOR}_{sep}/70680)^{-0.8207}$$

A.5. Ovalle Correlation

$$\ln P_d = 0.00477\ \mathrm{Sum}\ X^2 + 0.32239\ \mathrm{Sum}\ X + 8.48$$

$$X = \ln \mathrm{GORsep\_}X + \mathrm{API\_}X + \gamma_{gd}\_X$$

$$\ln \mathrm{GORsep}\ \_X = -0.01691(\ln \mathrm{GOR}_{sep})^2 - 0.87528(\ln \mathrm{GOR}_{sep}) + 9.8895$$

$$\mathrm{API\_}X = 0.00151\ (\mathrm{API})^2 - 0.29709(\mathrm{API}) + 11.7$$

$$\gamma_{gd}\_X = -0.81744(\gamma_{gd})^2 - 2.91450(\gamma_{gd}) + 3.5202$$

Appendix B. Statistical parameters

The following statistical means are used to determine the accuracy of the correlations.

B.1. ARE: average percent relative error

$E_r = \left(\frac{1}{n_d}\right)\sum_{i=1}^{n_d} E_i \qquad E_i = \frac{(x_{\exp} - x_{est})}{x_{\exp}} \cdot 100, \quad i = 1, 2, \cdots, n_d$

B.2. AARE: average absolute percent relative error

$E_a = \left(\frac{1}{n_d}\right)\sum_{i=1}^{n_d} |E_i|$

B.3. $AARE_{min}$ and $AARE_{max}$: minimum and maximum absolute percent relative errors

$E_{\min} = \min_{i=1}^{n_d} |E_i| \qquad E_{\max} = \max_{i=1}^{n_d} |E_i|$

B.4. S^2: standard deviation. It is expressed as a positive square root of the variance

$S^2 = \left(\frac{1}{n_d - 1}\right)\sum_{i=1}^{n_d} (E_i - E_r)^2$

B.5.E_{rms}: the root mean square error

$E_{rms} = \sqrt{\frac{\sum (E_i)^2}{n}}$

B.6.*r*: the correlation coefficient. The other term is the coefficient of determination, r^2, which is simply the square of the correlation coefficient which is defined by:

$r^2 = 1 - \frac{\sum_{i=1}^{n_d} (x_{\exp} - x_{est})_i^2}{\sum_{i=1}^{n_d} (x_{\exp} - \bar{x})_i^2} \qquad \text{where, } \bar{x} = \frac{1}{n_d}\sum_{i=1}^{n_d} (x_{\exp})_i$

Appendix C. Nomenclature

List of symbol description	
API	stock tank oil API gravity
GOR_{diss}	dissolved gas to oil ratio, SCF/STB
GOR_{sep}	separator gas to oil ratio, SCF/STB
Ln	natural logarithm (base e)
M_{C7+}	the molecular weight of heptanes plus
P	pressure
P_{ci}	critical pressure of component i, psia
P_d	dew point pressure, psia
P_{pc}	pseudocritical pressure, psia
P_{pr}	pseudoreduced pressure of the gas mixture, psia
P_{sep}	separator pressure, psia
R	universal gas constant
R_{sep}	separator producing gas–oil ratio, scf/SP bbl
T	temperature
T_{ci}	critical temperature of component i, °R
T_{pc}	pseudocritical temperature, °R
T_{pr}	pseudoreduced temperature of the gas mixture, °R
T_R	reservoir temperature, °R
T_{sep}	separator temperature, °R
V	molar volume
$(V_g)_{sep}$	volume of separator gas at separator condition, cc
$(V_g)_{sc}$	volume of separator gas at standard condition, cc
Y_{Ci}	mole fraction of component i in the gas mixture
Z_{sep}	super compressibility factor of separator gas
A	dimensionless factor
γ_{C7+}	specific gravity of heptanes-plus fraction (air = 1.0)
γ_{diss}	average specific gravity of dissolved gas (air = 1.0)
γ_{sep}	average specific gravity of separator gas (air = 1.0)
γ_{gd}	specific gravity of reservoir gas
β_g	separator gas formation volume factor
List of subscripts	
C_{7+}	property of heptanes plus fraction
C_i	mole fraction of component C; in gas mixture
D	dew point
Diss	dissolved gas
G	gas
P_c	pseudocritical
Pr	Pseudoreduced
Sc	standard condition
Sep	separator

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